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The high-frequency scattering of the S0 Lamb mode by a circular blind hole in a plate

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Abstract

The scattering problem of an incident high-frequency S0 Lamb wave in a plate with a circular blind hole is investigated. The study is not limited to the low-frequency range of this wave, in which the popular approximate plate theories are inapplicable. A 3D analytical approach is used where the wave fields are expanded in all possible Lamb modes, including propagating and evanescent modes. Due to the non-symmetric blind hole defect, the scattered fields will contain higher order converted modes in addition to the fundamental S0 and A0 modes. The far field scattering amplitudes of various propagating Lamb modes for different hole sizes are inspected. The results are compared with those of low frequencies and some different phenomena are found.

Keywords: High frequency Lamb wave; 3D scattering; Mode conversion; NDT

1. Introduction

The use of guided Lamb waves for the non-destructive testing (NDT) of large plate structures has been the subject of much investigation in recent years[1-2]. Lamb waves are very suitable for rapid inspection of defects because they can propagate large distances without significant attenuation along the plate and may be scattered by any defects. In order for Lamb waves to detect defects in plates, it is important to characterize the scattering of these waves by defects. Strong scattering and mode conversions provide worthy information about the nature of the defects.

The problem of Lamb wave scattering at different types of defects has been well explored in the literature[3-6]. Diligent *et al.* [3] presented a study of the low-frequency reflection and scattering of the S_0 Lamb mode from a circular through-thickness hole in a plate. Grahn[4] studied Lamb wave scattering from a circular partly through-thickness hole in a plate using exact 3D approach and plate theory approach based on the Poisson/Kirchhoff plate

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theory. Cegla, Rohde and Veidt [5] extended Grahn's Poisson/ Kirchholf model [4] to the Poisson/ Mindlin model. Moreau and his collaborators [6] investigated the three-dimensional (3D) scattering of guided waves by the cavities with irregular shape in an isotropic plate. The above studies predominantly concentrated on the scattering modeling for low frequency in which a Lamb mode is incident in a frequency range below the A1. Relatively less work has focused on the scattering modeling for higher frequency where the plate theory models are not valid and the exact 3D theory must be used. It is well known that the 3D model is rather unwieldy for characterizing the interaction of Lamb waves with structural defects. However, the resolution and the sensitivity to defects requirements normally force the frequency of choice is as high as possible. Higher frequency guided Lamb waves offer a trade-off between smaller monitoring range and improved sensitivity for small defects[7].

The work presented here is to extend the knowledge of the interaction of the Lamb waves with defects from the low frequency to the higher frequency. A 3D model based on the solutions of Rayleigh-Lamb and SH equations [4] is used, which apply not only for the low frequency range, but also for higher frequency. The far field scattering amplitudes of each propagating mode for different hole radii at the frequency above S1 mode cut-off frequency but below S2 mode cut-off frequency are given. The numerical results are compared with those of the low frequency. The scattering phenomena are expected to be different from the case of low frequency incidence.

2. Wavenumber solutions used in 3D theory

The 3D theory model for the scattering problem of an incident S0 Lamb wave in an isotropic plate with a non-symmetric blind hole has been described by Grahn[4].The same approach is followed here, however, the incoming field is given by a plane S0 Lamb wave at the frequency higher than the A1 mode cut-off frequency. Group dispersion curves for the well-known Lamb waves and SH waves in a steel plate are shown in Fig.1, which indicate the speed of propagation of a wave packet, where the axis of abscissas is plotted as frequency-thickness product. In Fig.1(a), it can be seen that there are four propagating Lamb modes at the frequency thickness product *fd*=3MHz mm. These modes are S0, A0, S1 and S2, respectively. Because the scattering problem is 3D, SH-waves are also be contained in scattered field. In Fig.1(b), at the *fd*=3MHz mm, there are propagating SH0 and SH1 modes. It is possible in principle for these modes to be excited by mode conversion when an S0 wave is incident at a defect. Thus, the wave fields will be expressed as superpositions of multi Lamb modes and SH modes, both propagating and nonpropagating modes, whose wavenumbers are computed according to the Rayleigh-Lamb and SH equations.

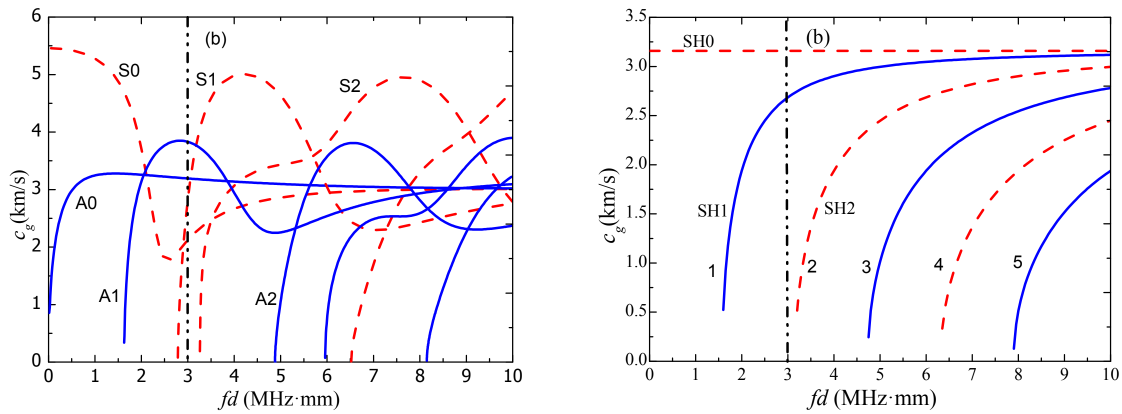

Fig. 1. Group velocity dispersion curves for a steel plate: (a) Lamb waves; (b) SH waves.

3. Results and discussion

The steel plate of thickness d=2h=2mm with Young's module E=210GPa, Poisson's ratio ν =0.3 and density

$\rho = 8100 kg/m^3$ is used in the numerical examples. The incoming field is a plane S0 wave. The blind hole depth is half the plate thickness. Since the wave fields are expressed as superpositions of propagating and evanescent Lamb modes and SH modes in 3D approach, wavenumbers of these modes can be obtained by the roots of Rayleigh-Lamb and SH modes[4]. Assuming 10 symmetric Lamb modes, 10 asymmetric Lamb modes and 10 SH modes participate in the calculations, wavenumres of various modes at high frequency *f*=1.5MHz are shown in Table 1, corresponding to frequency thickness products *fd*=3MHz mm and 3MHz mm. In Table 1, the symmetric and asymmetric Lamb modes are abbreviated to S and A, respectively, and k_i (i=0~9) are the wavenumbers of Lamb modes and l_i (i=0~9) are the wavenumbers of SH modes. The real wavenumbers represent the propagating waves and the complex wavenumber represent the evanescent waves. Notice that there are propagating S0, A0, S1, A1, SH0 and SH1 modes, the rest are nonpropagating modes.

Table 1. Wavenumbers of various modes at the frequency *f*=1.5MHz (*fd*=3MHz mm)

Modes	k_0 (l_0)	k_1 (l_1)	k_2 (l_2)	k_3 (l_3)	k_4(l_4)	k_5(l_5)	k_6(l_6)	k_7(l_7)	k_8(l_8)	k_9(l_9)
S	2896	1687	352i	1584+ 4752i	1795+ 8175i	1943+ 11439i	2056+ 14658i	2149+ 17837i	2227+ 21011i	2295+ 24176i
A	3387	1594	1424+ 2807i	1701+ 6499i	1874+ 9816i	2000+ 13060i	2105+ 16246i	2190+ 19425i	2262+ 22595i	2326+ 25757i
SH	2985	2538	981i	3647i	5529i	7265i	8940i	10583i	12207i	13819i

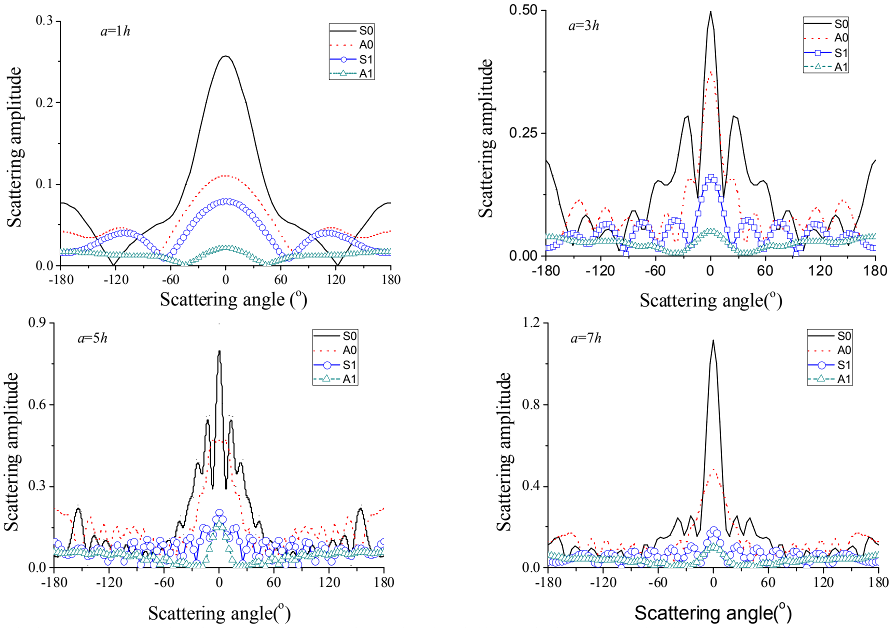

Fig.2. Far filed scattering amplitudes of various Lamb modes for different hole radii at the frequency *f*=1.5MHz (*fd*=3MHz mm).

At the frequency *f*=1.5MHz, far filed scattering amplitudes in all directions of various Lamb modes for varied hole radii are shown in Fig.2. The absolute magnitudes of all the scattered wave increase as the hole radius increase. The scattered S0 mode has larger amplitudes than A0 mode in the forward scattering directions, about -60 to 60 degrees. This is different from the case of the low-frequency in which the converted A0 mode has great influence on the scattering wave fields [4]. It can also be seen that the converted higher order S1 and A1 modes keep low amplitude levels compared with S0 and A0 modes. The scattered SH0 and SH1 modes are not illustrated in Fig.2 so as to show clearly the results.

4. Conclusions

This study presents a theoretical investigation of the scattering of the high frequency S0 Lamb mode from a circular blind hole defect in a plate based on the 3D approach developed by Grahn[4]. The 3D approach can provide accurate results even for higher frequencies but more terms are required in the expansions of the wave fields. Just because of this, most researchers have focused on rather low frequencies. However, in this paper we investigate the scattering problem when the S0 wave is incident at the frequency above the S1mode cut-off frequency but below the S2 mode cut-off frequency. Thus, the scattering fields will contain six propagating modes as S0, A0, S1, A1, SH0 and SH1which would result in a complex calculation. Therefore, low frequency results are given to show the validity of the 3D calculation on the one hand, and on the other hand, these results are used for comparisons with higher frequency results. It is found that the S0 mode has the considerable amplitudes in the forward scattering compared to other propagating Lamb modes as A0, S1 and A1 at the higher frequency. This is quite difference from the case of the low frequency, where the converted A0 mode is dominant in all scattering directions. It is also noticed that the S1 mode has larger amplitudes than A0 mode in the forward scattering direction when the hole radius is very small.

Acknowledgements

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References

[1] Chen, X., Michaels, J. E., Michaels, T. E., 2015. A methodology for estimating guided wave scattering patterns from sparse transducer array measurements. IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control 62 (1), 208-218.

[2] McKeon, P., Yaacoubi, S., Declercq, N. F., Ramadan, S., Yaacoubi, W. K., 2014. Baseline subtraction technique in the frequency-wavenumber domain for high sensitivity damage detection. Ultrasonics 54, 592-603.

[3] Diligent, O., Grahn, T., Boström, A., Cawley, P., Low, M. J. S., 2002. The low frequency reflection and scattering of the S_0 Lamb mode from a circular through-thickness hole in a plate: Finite Element, analytical and experimental studies. J. Acoust. Soc. A. 112 (6): 2589-2601.

[4] Grahn,T., 2003. Lamb wave scattering from a circular partly through-thickness hole in a plate. Wave Motion 37, 63-80.

[5] Cegla, F. B., Rohde, A., Vedit, M., 2008. Analytical prediction and experimental measurement for mode conversion and scattering of plate waves at non-symmetric circular blind holes in isotropic plates. Wave Motion 45, 162-177.

[6] Moreau, L., Caleap, M., Velichko, A., Wilcox, P. D., 2012. Scattering of guided waves by flat-bottomed cavities with irregular shapes. Wave Motion 49, 375-387.

[7] Chan, H., Masserey, B., Fromme, P., 2015. High frequency guided ultrasonic waves for hidden fatigue crack growth monitoring in multi-layer model aerospace structures. Smart Mater. Struct. 24, 025037